010588-34-F

THE UNIVERSITY OF MICHIGAN
COLLEGE OF LITERATURE, SCIENCE AND THE ARTS
DEPARTMENT OF PSYCHOLOGY

Final Report

INTELLECTUAL PERFORMANCE UNDER STRESS

Robert G. Pachella
Project Director

DRDA Project 010588

Under contract with:
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BEHAVIORAL SCIENCES DIVISION
CONTRACT NO. F44620-72-C-0019

Sponsored by:
ADVANCED RESEARCH PROJECTS AGENCY
ARPA Order No. 1949

September, 1976

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR - TR - 77 - 0313	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INTELLECTUAL PERFORMANCE UNDER STRESS.		5. TYPE OF REPORT & PERIOD COVERED Final Report. 1 Oct 1971 — 30 Jun 76
		6. PERFORMING ORG. REPORT NUMBER 010588-34-F
7. AUTHOR(s) Robert G. Pachella		8. CONTRACT OR GRANT NUMBER(s) F44620-72-C-0019, ARPA Order - 1949
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Michigan, Human Performance Center, Department of Psychology, Ann Arbor, Michigan		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61101E/AO 1949
11. CONTROLLING OFFICE NAME AND ADDRESS Advanced Research Projects Agency, 1400 Wilson Blvd, Arlington, Virginia 22209		12. REPORT DATE Sep 1976
		13. NUMBER OF PAGES 51
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Air Force Office of Scientific Research (NL), Bolling AFB DC 20332		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited. (12) 56p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Stress
Information overload
Speed stress
Motor performance
Information processing test battery

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the Final Technical Report on Contract F44620-72-C-0019 between the Advanced Research Projects Agency, Department of Defense, monitored by the Air Force Office of Scientific Research, and the Human Performance Center, Department of Psychology, University of Michigan, for research on Human Information Handling Processes during the period 1 October 1971 to 30 June 1976. The report lists the products of contract work: 41 technical reports published and 25 oral presentations

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unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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at scientific meetings. Major accomplishments are summarized under the general headings of (a) State (of the organism) Variables (b) Information Overload (c) Speed Stress and (d) a Test Battery of Human Performance.

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I. OBJECTIVES OF THE CONTRACT PROGRAM

This is the final report of research supported by the Advanced Research Projects Agency, United States Department of Defense, and monitored by the Air Force Office of Scientific Research under contract F44620-72-C-0019, with the Human Performance Center, Department of Psychology, University of Michigan. The period of this contract work was from 1 October 1971 to 30 September 1975. The contract was extended, without additional funding, from 1 October 1975 until 30 June 1976.

This contract continued ~~the~~ research programs at the Human Performance Center, which was funded from 1 June 1963 ~~through~~ 31 May 1967 under contracts AF 49(638)-1235 entitled Human Performance in Information Handling and Storage, and from 1 June 1967 through 31 August 1971 under
and contract AF 49(638)-1736, entitled Human Information Handling Processes. One of the general objectives of the original contracts and the present contract was to establish, in a University environment, a permanent research facility for the investigation of human performance capabilities and limitations that are of importance for the performance of men in a wide variety of man-machine systems. With the support for such an effort by these contracts, the Human Performance Center of the Department of Psychology, University of Michigan, was established in 1963 and has now become a stable federation of experimental and mathematical psychologists interested in advancing knowledge about man's information processing activities in sensing, perceiving, remembering, skillful manipulation of controls, and problem solving. The effort within this the present contract program has been directed more and more to the perceiving and remembering functions, with increasingly heavy emphasis on cognitive and intellectual factors and skills.

Since October 1, 1971 continued progress has been made in the study of component mental activities that play an important role in reliable, efficient performance of military operational duties. These activities have been studied in isolation and under stressful conditions. Our investigations have focused on stress resulting from excessive task demands such as tasks requiring information overload, unrealistic requirements for speed or precision and the need to conduct two or more relatively independent activities concurrently. Our goal was to identify the differential susceptibility of the component skills to the effects of stress, to suggest training procedures for producing resistance to such stress effects and to define principles of man-machine system design that will minimize the incidence of stress-produced decrements in performance.

Throughout the contract period, the following objectives were pursued:

1. Conduct research to assess the effect of speed stress, memory overload, and other task-induced stressors on performance of a range of human information processing tasks.
2. Formulate principles of human reactions to stress that have implications for equipment or job design, for development of training programs or training aids or for the selection and assignment of military personnel.
3. Conduct research on the relationship between the performance of elemental information processing activities and the performance of integrated skilled activities of the kind required in a military setting.

II. Participating Scientists

The supervision, direction and responsibility for the research conducted on this project has fallen largely upon the senior staff of the Human Performance Center. All members of the Center are full-time faculty of the department of Psychology Department of the University of Michigan. Many other people have also made significant contributions to the work on the project. These people consist mostly of junior scientists who are either full-time graduate students in either the Experimental Psychology program or in the Mathematical Psychology program. Additionally, a number of undergraduate research assistants have also participated. A listing of all of the participants in the project is given below.

Senior Scientists -- During the period of this contract the staff of the Human Performance has undergone an unusual amount of turnover. From the beginning of the project to the present, only Pachella has been actively involved during the entire period. Listed below are the original members of the project staff with their dates of participation. Following this are the other scientists that have participated.

Original Staff	Dates of Participation
Robert A. Bjork (Now Professor at U.C.L.A.)	Oct 71 - July 74
James G. Greeno (Now Professor at Univ. of Pittsburgh) Co- principal investigator 1974-5	Oct 71 - April 75
Edwin J. Martin (Now Professor at Univ. of Kansas) Co-principal investigator 1971-4	Oct 71 - Aug 74
Robert G. Pachella (Assoc. Prof.) Co-principal investigator 1973-5 Project Director 1974-5	Oct 71 - June 75

Richard W. Pew (Now at Bolt, Baranek & Newman, Inc.) Co-principal investigator 1971-4 Project Director 1971-4	Oct 71 - July 74

<u>Additional Staff</u>

E. Bjork (Now Assoc. Prof. at U.C.L.A.)	Oct 72 - Oct 74
John Jonides (Asst. Prof)	Oct 75 - June 76
Judith Reitman (Assoc. Prof.)	June 74 - June 76
J.E. Keith Smith (Prof.)	Oct 74 - June 76
Ewart Thomas (Now Professor at Stanford Univ.)	Oct 72 - Sept 73
Daniel J. Weintraub (Prof.)	Oct 72 - April 75

<u>Junior Scientists</u> -- Junior scientists consist of graduate and undergraduate research assistants. Ten graduate student assistants earned doctoral degrees with thesis work directly related to and supported by the ARPA contract. They are listed below along with their current position. Nineteen other graduate students worked on the project but did not or have not yet completed their doctoral requirements. Seventeen undergraduate assistants also participated on work of the subject contract and a number of these -re currently enrolled in graduate programs around the country. Taken together these lists constitute a demonstration of the important "filter down" impact of money spent on the current project. Most of these students are still engaged in significant research of the type that was initiated by their project work. Thus, the total research contribution of the present contract will continue to provide dividends far into the future.

Students Completing Doctorate	Present Position
Richard Jagacsinski	Asst. Prof. Ohio State Univ.
Robert Jongward	Univ. of Michigan Med. Sch.
David Kieras	Asst. Prof. Univ. of Arizona
Richard Mayer	Asst. Prof. Univ. Cal at Santa Barbara
Jeffery Miller	Asst. Prof. Univ. Cal. San Diego
Donald Polzella	Asst. Prof. Univ. of Dayton
Andrew Rose	American Institute of Research
Douglas Stokes	
William Whitten	Asst. Prof. State Univ. New York at Albany
Christopher Wickens	Asst. Prof. Univ. Illinois

Pre-doctoral Students

Edward Adelson
Randall Alexander
Nancy Bellows
Pat Cheng
Michael Donnell
Mary Hardzinski
Janice Johnson
Cecile Johnston
David King
Clayton Lewis
Kathrine McKeithen
Mathew Olson
John Patterson
Michael Sivak
Patricia Somers
Keith Stanovich
Christopher Stiehl
Kirby Thomas
Charles Wright

Undergraduate Research Assistants

David Bauer

Laurie Birenbaum

Seth Chaiklin

Phillip Dixon

Elizabeth Engelmann

Marcia Gershenson-Zukowski

Karen Goldstein

Joel Gurin

Any Horowitz

Ellen Issacson

James Kincaid

Phyllis McClure

David Noreen

Mark Pittell

Marion Selz

Brian Wandell

Peter Ward

III. PUBLICATIONS

During the course of the project 41 publications have been issued which are related to project work. These include twenty journal articals, seven book chapters, eleven Human Performance Center Technical reports of original research, and three technical reports of a managerial nature. Because of publication lag five of these reports are still in press and are not available at the time of this final report. At least six other manuscripts containing reports of ARPA sponsored research are still in preparation at the time of this writing. They are not included under the listing of published work, but should they be accepted for publication they will carry the standard acknowledgement of ARPA support. There also exists, on hand, data which was collected, summarized and analysed with the aid of support of the present contract that will undoubtedly lead to additional publications, but which at this time have not yet led to enough of a definitive statement about some problem to merit the production of a written report. Again, at the time of future inclusion of any of this material in published articles, adequate acknowledgement of ARPA support will be made.

Following the list of written publications is a list of oral presentations concerning contract research that were presented at scientific meetings. These oral reports include only those that were made at meetings for which a published, archival program or proceedings have been issued. Numerous other oral presentations have been made by the members of the staff concerning project research for which no archival record exists. These include Colloquia, conferences and meetings at individual university or industrial settings. They have of course, served well the dessemation of the research produced under the present contract.

Finally, in October, 1972 a Conference was held in Ann Arbor on Human Performance and Stress in order to acquaint various military services

behavioral science and human engineering activities with the work of the present project. The list of participants in the conference and the program of presentations is presented. The main goal of the conference was to promote the interchange of information relating basic research on human performance to the needs of the military services. All of the participants from the various military services agreed that this purpose was accomplished.

PUBLICATIONS ISSUED SINCE OCT 1, 1971
(CONTRACT f44620-72-C-0019)

Bjork, R.A. Short-term storage: The ordered output of a central processor. Chapter in Theoretical developments in cognitive psychology, Vol. I. F. Restle (Ed.), Lawrence Erlbaum Associates, Hillsdale, N.J., 1975. (010588-28-B)

Bjork, R.A. Theoretical implications of directed forgetting. Chapter in Coding Processes in Human Memory. A. W. Melton & E. Martin (Eds.), Washington D.C., 1972. (010588-17-B)

Bjork, R.A. The updating of human memory. In G. Bower (Ed.) Psychology of Learning and Motivation, Vol. 11, in press.

Chananie, J.D. Memory effects in visual search: The graticule. Human Performance Center Technical Report No. 34, December, 1971 (010588-01-T)

Elmes, D.G., & Bjork, R.A. The interaction of encoding and rehearsal processes in the recall of repeated and nonrepeated items. Journal of Verbal Learning and Verbal Behavior, 1975, 14, 30-42. (010588-27-J)

Kieras, D. A general experiment programming system for the IBM 1800. Behavioral Research Methods and Instruction 1973, 5, 235-239. (010588-08-J

Kieras, D. Analysis of the effects of word properties and limited reading time in a sentence comprehension and verification task. No. 53, August, 1974. (010588-22-T)

King, D.R.W. and Anderson, J.R. Long-term memory search: An intersecting activation process Journal of Verbal Learning and Verbal Behavior, in press.

Martin, E. Stimulus encoding in learning and transfer. Chapter in Coding Processes in Human Memory. A.W. Melton & E. Martin (Eds.), Washington, D.C., 1972. (010588-18-B)

Martin, E. Generation-recognition theory and the encoding specificity principle. Psychological Review, 1975, 82, 150-153.

Martin, E. Serial learning: A multilevel access analysis. Memory and Cognition, 1973, (010588-15-J)

Martin, E.J., & Pew, R.W. Semi-annual technical report, April 30, 1972. (010588-07-SA)

Mayer, R.E. Acquisition and resilience under test stress of structurally different problem solving procedures. Human Performance Center Technical Report No. 42, May, 1973. (010588-09-T)

Mayer, R.E. Acquisition processes and resilience under varying testing conditions for structurally different problem-solving procedures. Journal of Educational Psychology, 1974, 66, 644-656. (010588-24-J)

Mayer, R.E. and Greeno, J.G. Effects of meaningfulness and organization on problem solving and computability judgments. Memory and Cognition, 1975, 3, 356-362. (010588-31-J)

Mayer, R.E., Stiehl, C.C., and Greeno, J.G. Acquisition of understanding and skill in relation to subjects' preparation and meaningfulness of instruction. Journal of Educational Psychology, 1975, 67, 331-350. (010588-31-J)

Miller, J.O. Effects of stimulus probability on encoding mechanisms in information processing tasks. Human Performance Center Technical Report No. 56 (010588-33-T)

Miller, J.O., & Pachella, R.G. On the locus of the stimulus probability effect. Journal of Experimental Psychology, 1973, (010588-11-J)

Miller, J.O. and Pachella, R.G. Encoding processes in memory scanning tasks. Memory and Cognition, 1976, 4, 501-506

Pachella, R.G. The effect os set on the tachistoscopic recognition of pictures. In P.M.A. Rabbitt and S. Dormic (Eds.) Attention & Performance V. Academic Press: New York 1975, (010588-12-M)

Pachella, R.G. The interpretation of reaction time in information processing research. Human Performance Center Technical Report No. 45, November, 1973. (010588-13-B)

Pachella, R.G. Annual Report, July 1, 1974 - June 30, 1975. (010588-32-A)

Pachella, R.G. Final Report: Intellectual performance under stress.

Pachella, R.G., & Fisher, D. Hick's Law and the speed-accuracy trade-off in absolute judgment. Journal of Experimental Psychology, 1972, 92, 378-384. (010588-04-J)

Pachella, R.G., & Miller, J.O. Stimulus probability adn same-different classification, Perception and Psychophysics, 1976, 19, 29-34.

Pew, R.W. Human perceptual-motor performance. Chapter in Human information processing: Tutorials in performance and cognition. B.H. Kantowitz (Ed.), Lawrence Erlbaum Associates, Washington, D.C., 1974. (010588-20-B)

Pew, R.W. Levels of analysis in motor control. Brain Research, 1974, 71, 393-400. (010588-26-J)

Polzella, D.J. The effect of sleep-deprivation on short-term recognition memory. Human Performance Center Technical Report No. 47, April, 1974. (010588-19-T)

Polzella, D.J. Remembering the functional sentence. Human Performance Center Technical Report No. 39, August, 1972. (010588-06-T)

Polzella, D.J., & Martin, E. Stimulus encoding in A-B, A-D transfer. American Journal of Psychology, 1973, 86, 589-600. (01058814-J)

Reitman, J.S. Skilled perception in Go: Deducing memory structure from response times. Cognitive Psychology, in press.

Rose, A.M. Human information processing: An assessment and research battery. Human Performance Center Technical Report No. 46, January, 1974. (010588-16-T)

Stanovich, K.and Pachella, R.G. The effect of stimulus probability on the speed and accuracy of naming alphnumeric stimuli. Bulletin of the Psychonomic Society, in press.

Stokes, D.M. Anxiety level and tolerance in cognitive inconsistency. Chapter V of Pacification theory: A mathematical theory of cognitive consistency. Doctoral dissertation, 1974. (010588-25-T)

Thomas, E.A.C. The selectivity of preparation. Psychological Review, 1974, 81, 442-464. (010588-23-J)

Walter, D.A. The role of acoustic and semantic dimensions of memory in sentence memory and comprehension. Human Performance Center Technical Report No. 36, March, 1972. (010588-03-T)

Wattenbarger, B.L., & Pachella, R.G. The effect of memory load on reaction time in character classification. Perception & Psychophysics, 1972, 12, 100-102. (010588-05-J)

Weintraub, D.J., & McNulty, J.A. Clarity versus identifiability of repeatedly flashed patterns. Journal of Experimental Psychology, 1973, 99, 293-305. (010588-10-J)

Wichawut, C. Encoding variability and the effect of spacing of repetitions in continuous recognition memory. Human Performance Center Technical Report No. 35, January, 1972. (010588-02-T)

Wickens, C.D. The effects of time sharing on the performance of information processing tasks: A feedback control analysis. Human Performance Center Technical Report No. 51, August, 1974. (010588-21-T)

Presentations at Scientific Meetings

Bjork, Elizabeth, L., Bjork, Robert, A., & Glenberg, Arthur, Reinstatement of Interference Owing to To-Be-Forgotten Items. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1973.

Bjork, Robert., Discussant and Moderator. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1973.

Bjork, Robert, A., & Whitten, William B., A Revelation of Formerly Unreavealed Retrieval Processes in Long-Term Free Recall. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1972.

Bjork, Robert, A., The Updating of Memory. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1974.

Greeno, J.G., Structural Representations in Working Memory. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1973.

Greeno, James, G., Organization of Problem Solving: Choice of Subgoals Based on Results of Search for Information. Paper presented to the Psychonomic Society, Denver, Colorado, November, 1975.

Hardzinski, Mary, & Pachella, Robert, G., Stimulus Representation in Character Classification. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1976.

Kieras, David, Effects of Word Properties on Comprehension and Verification of Sentences. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1975.

Martin, Edwin, Origin of the Serial Position Effect in Memory for Sequences. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1973.

Martin, Edwin, Locus of Repetition Effects in Serial Learning. Paper presented to the Psychonomic Society, Boston, Massachusetts, November, 1974.

Martin, Edwin, Subjective Organization in Traditional Serial Learning. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1972.

Martin, Edwin, Memory Codes and Negative Transfer. Paper presented to the Midwestern Psychological Association, Cleveland, Ohio, May, 1972.

Martin, Edwin & Polzella, Donald, J., Stimulus Recording in Transfer Learning. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1971.

Miller, Jeffery O., & Pachella, Robert G., The Locus of Effect of Stimulus Probability on Memory Scanning. Paper presented to the Midwestern Psychological Assocation, Chicago, Illinois, May, 1973.

Pachella, Robert, G., Memory Scanning Under Speed Stress. Paper presented to the Midwestern Psychologica Association, Cleveland, Ohio, May, 1972.

Pachella, Robert G., "Same Different" Classification and the Speed-Accuracy Tradeoff. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1972.

Pachella, Robert, G., Additive Factors and Under additivity within Stimulus Encoding Processes. Paper presented by the Midwestern Psychological Association, Chicago, Illinois, May, 1976.

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Pew, Richard W., Baum, David, R. & Patterson, John, F., Human Information Processing in Ann Arbor and on Pike's Peak. Paper presented to the Psychonomic Society, Bostion, Massachusetts, November, 1974.

Pew, Richard W., & Wickens, Christopher, D., The Attention Demands of Highly Practiced Movements. Paper presented to the Psychonomic Society, St. Louis, Missouri, November, 1972.

Reitman, Judith, S., Skilled Perception in Go: Deducing Memory Structures from Response Times. Paper presented to the Psychonomic Society, Denver, Colorado, November, 1975.

Stanovich, Keith, E., & Pachella, Robert, G., The Effect of Stimulus Probability and Stimulus Quality on Reaction Time Tasks with 1 to 1 S-R Mappings. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1974.

Stanovich, Keith E., Smith, J.E.K. & Pachella, R.G., An Analysis of Confusion Errors in Naming Letters under Speed Stress. Paper presented to the Psychological Association, Chicago, Illinois, May, 1975.

Walter, Donald, A., The Effects of Massed versus Distributed Practice in Phonemic and Semantic Dimensions of Recognition Memory. Paper presented to the Midwestern Psychological Assocation, Chicago, Illinois, May, 1973.

Wright, Charles, E., & Pachella, Robert, G., Rehearsal Controlled Stimulus Expectancy in a Sternberg Task: Evidence for a Mechanism which by passes Memory Scanning. Paper presented to the Midwestern Psychological Association, Chicago, Illinois, May, 1976.

Conference with Military Representatives

In October of 1972 a Conference on Human Performance and Stress was held to introduce the following eight representatives of the military services behavioral science and human engineering activities tc the work of the project:

Col. Austin W. Kibler	ARPA
Dr. Glen Finch	AFOSR
Dr. Julien Christensen	Air Force
Dr. Melvin J. Warrick	Air Force
Dr. Gordon Eckstrand	Air Force
Dr. Leon Katchmar	Army
Dr. Martin Tolcott	ONR
Dr. Robert Wherry	Navy

Presentations by project staff:

I. Robert A. Bjork
   - A. How to optimize memory input under overload conditions.
   - B. The "Scatterbrain" problem.

II. James G. Greeno
   - A. Problem solving under overload conditions.
   - B. Problem solving under speed stress.

III. Richard W. Pew
   - A. Time sharing stress and perceptual-motor performances.
   - B. Development of a battery of information processing tasks for the study of stress effects.
   - C. Training for the production of memorized movement patterns.

IV. Edwin Martin
   - A. Review of previous research on sleep loss and performance.
   - B. Sleep loss effects on recognition memory.

V. Robert G. Pachella
   - A. Speed Stress and information processing.
   - B. Effects of speed stress under sleep loss.

IV SUMMARY OF RESEARCH PROGRAM

As indicated above our research has focussed on what can be called psychological as opposed to environmental stressors. We have emphasized the impact of severe task demands such as speed stress and information overload. Initially our project also included work on sleeploss and anxiety but work of this type was not continued after the first year since our laboratories were not optimally efficient in conducting such research. The present section will summarize briefly the major findings that are contained in the previously listed publications.

In outline form this brief presentation of our research is divided into four sections. The first of these notes our exploratory attempts to investigate the organismic state variables of anxiety and sleep loss. The second section summarizes our extensive program of research on information overload variables. Here we discuss the control of information overload by way of general coding strategies as well as the particular mode of hierarchical coding. The role of information overload is also discussed with regard to motor performance. Section three summarizes our efforts to analyse the nature of speed stress. This extensive project has involved analytic studies for the purpose of establishing a general conceptualization of the information processing system utilized in speeded responding as well as studies that directly manipulate speed stress itself. Finally, we present a summary of our effort to develop a general test battery of human performance.

For the purpose of clarity in the discussion some references are cited that are not project work. All citations that indicate project work, however, have been underlines.

VARIABLES CONCERNING THE STATE OF THE OBSERVER

A. The interactive effect of anxiety and stress on the performance of cognitive tasks

Situational stress has different effects on the performance of simple and complex tasks by people of inherently relaxed and anxious natures. In our laboratory, a series of tasks were considered, from simple highly-learned responses (such as the classification of single letters either as vowels or consonants), and easy rote problem solving (such as the addition of a column of numbers) to complex problem solving and inference making. In each case, people who are rated as inherently anxious were compared to those inherently relaxed as they performed these tasks under normal and stressful circumstances.

When simple, highly-learned perceptual responses are to be made, anxious and relaxed people perform equally well, and react similarly to stress by speeding up their performance at the cost of increasing errors (Selz, 1973). When confronted with simple and complex problems to solve, however, inherently anxious people perform quite differently from those more relaxed. Relaxed people are unaffected by situational stress; they solve easy and difficult problems with equal facility under normal and stressful conditions. Inherently anxious people under stress, on the other hand, solve simple problems better than relaxed people and complex problems much worse (Mayer, Bjork, Pew, & Weintraub, 1973).

When listening to and trying to remember meaningful information in a stressful situation, people in general are less aware of any logical inconsistencies than they are normally. The stress is assumed to interfere with their automatic inference making abilities and organizational processes; they memorize the information rather than think about it and relate it to what they have already learned. Furthermore, those people who are highly anxious are not only unaware of the inconsistencies but also have a tendency

to selectively forget the inconsistent information. In contrast, relaxed people are able to remember both inconsistent and consistent information equally well, while still being unaware of the inconsistencies (Stokes, 1973)

This series of studies indicates that stress can be beneficial to the performance of well-learned, rote tasks (though at the natural cost of errors), but detrimental to the performance of tasks requiring memory and intelligence. In addition, when stressed, highly anxious people surpass relaxed ones in the performance of rote tasks such as adding columns of numbers, but essentially fall apart when faced with tasks requiring intelligence such as deciding among tactical moves or coordinating conflicting information from intelligence sources. These results make strong prescriptions for 1) significant reduction of stress when high-level cognitive tasks must be performed and 2) selection of personnel with inherently low levels of anxiety for the performance of higher level tasks, and assignments of inherently anxious people to well-learned rote tasks.

B. Effect of moderate sleep deprivation on memory and perceptual performance.

The original purpose of these studies was to investigate moderate levels of sleep loss on performance. Particular interest was paid to tasks involving simple acts of perceptual classification and recognition memory. These goals were dictated by practicality, since our laboratory was not equipped to study long-term sleep loss and since a number of simple perceptual and memorial tasks are amenable to sensitive theoretical analysis. The general literature on sleep loss indicates that two kinds of theory may be able to account for decrements in performance. On the one hand, there maybe a general loss in overall sensitivity leading to a consistent and constant loss of performance accuracy. On the other hand, sleep loss may have its effect in producing lapses of performance during which very little processing takes place which are intermixed with periods of normal sensitivity. Under this latter possibility increasing sleep deprivation simply leads to an increase in probability of

these lapses in performance.

The two major studies conducted in our laboratory have tended to support the latter position. Pachella and Selz (unpublished) looked at the effect of 24 hour sleep deprivation on the ability of subjects to perform a simple perceptual classification task. An important aspect of the study was the combination of the sleep loss manipulation with an emphasis on speed stress. This manipulation eliminates the possibility that sleep loss may reduce the cognitive capacity for performing tasks but that the (particular experimental) task is so simple that the reduced capacity does not appear as a decrease in performance. The emphasis on speed insures that performance decrements will show up as either a decrease in accuracy or by a decrease in response speed or both. The results of the study showed consistent, but very small effect of sleep deprivation. The small effects that did appear seemed to interact with increasing speed stress but the interaction did not achieve statistical significance. Apparantly, subjects under moderate speed stress are able to control the occurance of processing lapses well enough that simple tasks of short duration will not be affected.

The second study in our laboratory was conducted by Polzella (1974). This study looked at the effect of 24 hour sleep deprivation on the recognition memory for symbols similar to code groups. The design of the experiment was such as to allow the separation of true sensitivity effects from those of bias in emitting positive responses. The results showed that 24 hours of sleep deprivation reduced sensitivity. However, the latency associated with the subject's response clearly implicated that the decrease in performance was due to lapses in attention rather than a uniform decrement. This was true even though the input and recognition tests were administered at the operator's own pace. (i.e. when he said he was ready). Thus, performance decrements are associated with attentional fluctuation and active, creative duties will be less affected by sleep loss then

will be passive monitoring duties.

THE CONTROL OF INFORMATION OVERLOAD

A. Control through coding strategies

Intellectual performance does not operate in a vacuum; it requires holding in memory a number of different items of information. The items of information are the components from which one makes comparisons, draws conclusions, and arrives at decisions. Of central importance to effective and efficient performance is the capability to keep track of large numbers of things and to recall relevant information from past experience.

People are severly limited in the number of things they can keep in mind at once. Many situations present dractic overloads to the memory system. Our research on the efficient use of the memory system centers on isolating particular coding strategies used by performers faced with such overloads in different kinds of tasks. Coding strategies are subjective schemes or routines the operator uses to either group items of information together or selectively ignore certain kinds of items. The research has shown that what the operator does while attending the information determines how much he can retain and how long he can retain it. Markedly different coding strategies are appropriate, therefore, if the operator needs to retain information only momentarily than if he will be required to have continued access to that information for future decisions (Wichawut, 1972, Walter, 1972; Polzella and Martin, 1973; Martin, 1972; 1975).

When an operator must handle information that changes from moment to moment, as in the tasks of an air traffic controller or an aircraft dispatcher, information can be retained efficiently in a quick access, but limited and vulnerable store called short-term or working memory. We have been able to show in a series of studies that primary rehearsal, the rote repetition of presented material, is efficient in maintaining information in this short-term

memory (Bjork, 1972; 1975 Elmes & Bjork, 1975; Bjork & Allen, 19--). In addition, if moment to moment retention of a transient state is important, spatial tagging of the item's current status is additionally effective. (Bjork & McClure, in press)

These strategies are to be used for information needed for a short time only because they produce virtually no long-term trace. Both allow material to be discarded after such maintance ceases, making room for more incoming material. Whereas forgetting of material has often been viewed as the undesirable consequence of inadequate training or memorization, it now appears more appropriate to view it as a desirable process, one that allows succeeding information to be held in the same quick-access, limited-capacity store, without unnecessary, time-consuming accumulation in long-term memory.

If, on the other hand, the operator is required to later recall everything that transpired in a certain time period, rote rehearsal and spatial tagging are poor strategies. The operator would be better advised to provide mnemonic links among the items to be remembered by either creating a story around them or taking advantage of the meaningful structure from the task situation to link items together. The elaboration and inter-association of presented material with previously learned information from long-term memory is essential for the transfer of information to long-term memory. (Smith and Bjork, 19--). Such elaboration maximizes long-term retention, but is an inefficient strategy for situations requiring short-term recall, for they take too much time and clutter up long-term memory with/useles, potentially confusing information.

Furthermore, not only active coding strategies affect short and long-term retention differentially, but tests administered during the learning phase seem to create a similar pattern. We have been able to show that tests given during training that require involvement of long-term memory and some depth of processing can facilitate later recall. However, tests that involve simple,

shallow retrieval from short-term memory during the learning phase will have little effect on long-term retention (Bjork, 1975). The trainer can induce longer retention of material just by requiring the trainee to recall using his long-term memory associations rather than allowing him speedy but inconsequential recall from short-term memory.

Encoding also plays a strong role in the learning of how to solve computational problems. Given a problem requiring mathematical computation that can be taught either by rote algorithm or by stressing the understanding of concepts, we have found that individuals taught to compute them by rote could perform similar problems more easily than can those taught by concept. But, when generalizations beyound the problems given was required, then the concept-trained individuals excelled. However, when problem solving under time pressure was required, the overall efficiency decreased, but neither teaching procedure was to be preferred over the other (Mayer, 1973; Mayer & Greeno, 1975; Mayer, Stiehl, & Greeno, 1975.) These studies imply that unless all possible computational requirements can be anticipated and specifically trained, flight engineers and those with similar computationally oriented jobs should be trained to understand the concepts behind the calculations rather than to use memorized, specific algorithms.

Summary implications. These studies indicate that we are reaching a point where it is possible to optimize training procedures for virtually any kind of goal of memory performance in which the designer can adequately specify the desired performance. When the goal is immediate access to information needed for only a short time, rote rehearsal and spatial tagging are efficient ways to maintain information; when the goal is for long-term retention, some type of elaborate coding, reltions to concepts, or association with information already in long-term memory is highly effective.

B. Control of Information Overload by Hierarchical Coding

Simple learning of sequential and non-sequential material. When an operator is required to learn a check list or a fault diagnosing procedure, our research has shown that the learner partitions the sequence into definite, individualistic groupings within the sequence. The group boundaries are easily identifiable by their characteristics of being weak points, the points at which performances involve long delays or an outright error. As the learning progresses beyond establishment of these subgroups, links are then established between these subgroups, connecting the last item of one group to the first of the next (Martin, 1973). Thus, the learning process of serial sequences should be viewed hierarchically, proceeding from the mastery of the subsets to their serial integration into an overall structure. Consequently, during the teaching of sequential materials, it will be useful to build emphasis on structure and natural linkages among the related subsets wherever possible.

Similarly, if recall of the list of procedures is required under time stress, the nature of the performance breakdown, aside from being rather startling, is related to these subgroups the subject evolved during learning. The linkages between the subsets are most vulnerable to disruption; knowledge of the subsets themselves does not seem selectively impaired. Thus, it is especially important in the training sessions to establish the initial linkages, to unify the entire structure as solidly as possible and to provide supportive training for weak associative links on an individual basis.

These findings, suggesting that the learning process is inherently hierarchical, were extended from the learning of sequential material to the learning of an unordered collection of material. It has been shown that individuals naturally impose anorganization on material to be learned that capilalizes on known associations and groupings (Whitten, 1976). They adopt an organization and, as learning progresses, build on it. Furthermore,

learning to recall a group of related items can be enhanced by providing a structure or organizational scheme during learning. Presenting an organization reduces the burden of finding an organization and thus speeds learning the actual material. Second, after a delay, retention of the material that was presented in an organizational scheme is again superior to that of material presented without. After the elements that can be easily recalled are output as best as possible, recall of the organizational scheme itself then can help guide further retrieval of the missing elements. As in the case for sequential material, teaching unordered material should emphasize structure and natural linkages among related elements as much as possible.

Higher-level cognitive tasks. Emphasis then was shifted toward studies of higher-level cognitive tasks and the ways in which problem solvers deal with their limited memory capacities. It has been shown that experienced problem solvers, such as chess players, can code and remember vastly more game-related information than novices can. Thus, what amounts an example of extreme information overload for the novice is not for the master. Something the master does to the information allows him to transmit it through his limited capacity in ways unknown to the novice.

In our laboratories, we have been able to confirm and extend the finding of others, that this superiority of the experts is not due to greater memory capacity nor due to increased familiarity with the individual elements to be remembered; indeed, when shown situations where the placement of game pieces on a board is random, the experts do no better than the novices (Reitman, 1976). Increasingly, our studies have moved us to the conclusion that the expert relies on the direct perception of complex structure, on seeing and encoding subgroups and their interrelations. They see familiar subgroups and familiar groups of subgroups (a hierarchy), thereby reducing the mass of information presented to them into a few highly-known familiar units. They see two or three groups whereas the novice, unfamiliar with the way the individual

elements often appear together, is overloaded with information and can attend to and remember only a few low-level elements. Like the finding that learning is enhanced when it is organized hierarchically, it turns out that what distinguises an expert from a novice is his hierarchy of complex patterns in memory. An expert quickly perceives the structure in the situation; faced with the same mass of information, the novice, lacking this hierarchy, is quickly overloaded.

Like players of complex games such a chess, military strategists, photointerpreters, and computer operators, among others, utilize similar encoding strategies. Identification of the particular organizations, experts use knowing how the expert perceives a certain situation, should have important implications for training and job design in these kinds of cognitive activities.

Also, it appears from these studies that the expert relies as much on the direct perception of complex structure in the visual disply as he does on cognitive inferences about the nature and consequences of the situation. We already know that the perceptual system is highly sensitive to high order, interactive relations in sensory data. What the expert appears to do is transfer part of the control of complex decision making to the more efficient mode of perceptual analysis. This, of course, would have major implications for our concepts about the mode of display of the information necessary for the solution of complex problems. Often the various aspects of a problem are presented separately in the form of abstract numerical data, tables and charts. If expert problem solvers in fact "perceptualize" information, then this would suggest presentation of <u>integrated displays</u> where each variable of a problem would be mapped into a concrete dimension of a single spatial or temporal array. Thus, the problem solver could develop the ability to utilize the perceptual system in order to extract the correlational structure needed to arrive at a solution.

Retreival of facts When factual information is stored in long term memory, a network of connections among concepts is established. Retrieval of a specific fact may take more or less time, depending on the way in which components of the fact are related in memory and on the process used to retrieve the information, (King, and Anderson, 1976). We have studied effects of various structural features of information on the time taken to retrieve facts, and on the frequency of errors made when responses must be made quickly. Knowledge of the relationships between structure and retrieval time permits prediction of the kinds of questions on which people are likely to fail when they have little time for retrieval. A potential use of this knowledge is in guiding the organization of information (for example, in instructions or briefings) that will optimize the ease of retrieving facts of particular importance or facts that are likely to have to be retrieved in limited time or under other stressful conditions.

We have confirmed previous findings that information about categories is typically arranged in hierarchies, with more general properties stored at greater distance from specific instances than properties of the specific instances themselves. If a true statement contains ideas that are separated in the memory structure, more time is needed to retrieve the information. If a false statement contains ideas that are stored close to each other, then extra time will be taken before disconfirming information is retrieved. Additional time during retrieval occurs when there is an idea in a statement that is included in many facts stored in memory. And, we have found that a false statement takes longer to disconfirm if its two components come from propositions that share a common third idea than if its components come from unrelated propositions.

It has been shown that this effect of connectedness additionally holds for information in the form of equations whose terms are meaningful concepts, such as power = work/time, but not for nonsense information, such as K = W/D.

This suggests that the basic strategies of retrieving information are different in the two cases. When information stored in memory consists of relationships among concepts that are well understood, retrieval of factual information apparently involves a kind of activation spreading through the mental network of ideas, followed by a more analytic checking of the way in which ideas are related. Retrieval of information that is not meaningful to the operator seems to require a more systematic checking procedure, less susceptible to generation of false positives due to the presence of irrelevant connections among components elements.

One effect of speed stress on retrieval of confirming evidence is relatively simple and supports what would be expected intuitively: Errors increase most on items requiring retrieval of most information--that is, more errors occur when the subject must make an inference than when needed information is stored directly. However, the results regarding negative decisions are not as easily derived from intuition. The errors that occur most often under speed stress are mistaken positive responses to false statements involving ideas that are indirectly linked in memory. Speed stress also causes a general increase in errors for both true and false items containing ideas that are related to many other things in memory. The major conclusion is that retrieval of factual information involves a kind of activation spreading through the network of ideas stored in memory, followed by a more analytic checking of the way in which ideas are related. Ideas that are closely enough related to produce a connection in the memory structure are likely to generate false positives when fast performance is required, and a general degradation of performance will occur when many facts are known about elements included in the situation.

C. Motor control and information overload

During the past 5 yrs. the Human Performance Center has carried out a series of experiments designed to analyze the underlying components and representation of human skilled performance. This kind of analysis stands in contrast to the descriptive, normative approach to motor skills research of th 1950's and early '60's. A major contributing factor to the pursuit of analytic, explanatory models of skilled performance, aside from the general shift within experimental psychology to attempt to understand the processes underlying behavior, has been the successful application of feedback and control theory (Pew, 1974).

The picture of human perceptual-motor performance that has emerged from this program of experimentation is that of a system which has multiple levels of control and organization (Pew, 1974).

At the lowest level of control, an individual brings to bear on any skilled task a rudimentary servomechanism, a system that permits the generation of a stream of simple motor outputs that is responsive to perceived differences between a desired state and an actual state. An example of such a situation would be attempting to hold a constant force or tracking (see below) a random signal.

At an intermediate level of control is an individual's capacity to act on the basis of the coherence and predictability of the environment with which he is interacting. Most of the experiments summarized here deal with the performance of tracking tasks in which the subject controls a cursor attempting to keep it aligned with a moving target; the target is driven by a continous signal which may or may not have repeated properties. The major question concerns the nature of what is learned regarding signal repetitions.

Finally, the full richness of human skilled performance depends on capacities not captured by strict stimulus-bound representations derived from the study of tracking tasks. Instead it is embodied in voluntary movements,

typified by the ability to draw from the environment the appropriate initial conditions and to call up from memory integrated patterns of movement consonant with a desired goal. Further, individuals often encounter a complex set of heterogeneous tasks whose performance must be coordinated to result in stable systems output. This kind of multiple-task performance, called timesharing, is also organized at the highest levels of control. In our experiments we have used timesharing to reveal properties of perceptual-motor performance and in addition an experiment in which a feedback control analysis is applied to timesharing is summarized in this report.

Rather than conceiving of these three levels of control as independent, we should think of motor control in terms of a hierarchically organized system in which the distinction among levels is diffuse and in which there is a rich interplay among the various processes that the individual calls upon to complete a given task.

Tracking repeated and unrepeated signals

In these experiments (Pew, 1974 ; Baum & Pew, in preparation; Baum, Pew & Weintraub, unpublished data) subjects pursuit-tracked a continuous, random appearing 65 or 75 second signal. In actuality the signal was divided into three equal segments. Unbeknownst to the subjects, one of these segments was exactly the same from trial to trial, while the signal in the other two segments was unrepeated. Both the unrepeated and repeated segments were sampled from the same random process. In the course of 12 or more days of practice, overall tracking performance improved steadily. Performance on the repeated segment, however, improved more rapidly than performance on unrepeated segments and this improvement was only occasionally accompanied by subjects' reporting that they had detected a repeating pattern.

In one experiment the repeated sequence randomly appeared in one of the

three segments on each trial. Under these conditions, after some practice repeated sequence performance is superior regardless of segment, but an order effect (on performance) was revealed such that the first third of a trial was performed best and the last third worst. This result is interpreted in terms of muscle fatigue, a result of the tension necessary to achieve fine motor control over the movement of the cursor (Baum & Pew, in preparation).

In order to show something of the nature of what had been learned about the repeated sequence, subjects in some of the experiments tracked amplitude inversions of the signal after varying amounts of practice (Pew, 1974b; Baum & Pew, in preparation). The results of such transfer differ depending upon the nature of the unrepeated signals. In one experiment the unrepeated signals had a repeated character. They were randomly chosen "windows" on the same finite process (the repeated signal was the same window from trial to trial). Under these conditions transfer performance differed depending upon how the amplitude inversion was accomplished. When the entire signal was inverted transfer was positive; that is, performance on the inverted repeated sequence was better than that on unrepeated sequences. This is rather striking since tracking the inverted signal requires exactly opposite movements to those learned. When just the repeated signal was inverted, however, transfer was negative; now performance on the inverted repeated sequence was worse than unrepeated sequences. Thus we seem to have discovered an effect of context on tracking performance. That is, as long as the relative cues remain the same as when the entire signal is inverted, performance is relatively unperturbed. On the contrary, once the relationship between unrepeated and repeated sequences is disturbed, as when just the repeated sequence is inverted, performance is degraded. It is as if in this latter situation subjects have trouble "recognizing" the repeated sequence. (This analogy is only approximate since subjects in these experiments only

occasionally become aware of the presence of a repeated pattern.) This point of view predicts that under conditions where the unrepeated sequences are random, there should be no transfer to inverted sequences. Recently an experiment was completed which bears out this prediction (Baum, Pew & Weintraub, unpublished data).

Two other manipulations have yielded results consonant with classic findings in motor skill research (Baum & Pew, in preparation). In one experiment, subjects were trained using their right arms to control the cursor's position. After performance indicated a positive benefit due to repetition, these subjects transferred control to their left arms. A large positive transfer effect was observed. These results taken in combination with the earlier transfer studies indicate that what is learned is not at the level of specific motor commands (to a particular limb). The second manipulation of more traditional interest is that of determining the amount of retention of what is learned. Subjects in one experiment returned to the lab after 3 months and evidenced good long-term retention. This finding agrees well with previous research and the common lore that skills (e.g., bicycle riding) undergo very little forgetting.

Another issue that we have addressed using this general paradigm is the nature of the attention demands of performing the repeated sequence. An often-made assumption regarding motor performance is that with practice a skill comes to be automated, that is, it can be performed without the involvement of conscious attention. In order to explore this assumption empirically we ask subjects to perform the tracking task under timesharing conditions. If repeated sequence performance is automated, then one expects that performance to be unaffected by an additional task. Of course this requires that the additional task result only in capacity interference and not structural (i.e., sensory or motor) interference.

In one experiment (Pew, 1974) an attempt was made to assess any differential effects of memory load on tracking the repeated and unrepeated sequences. It

was shown that performance of a concurrent memory task (delayed repetition of auditorily presented words) significantly impaired tracking performance, but that tracking during the repeated sequence was no more resistant to interference than during unrepeated sequences. Also, performance of the memory task was worse during repeated sequences. These results in combination suggest that tracking the repeated sequence involves increased attention demands. This interpretation is complicated, however, by the instability of tracking task performance under timesharing conditions. Therefore, several other experiments were undertaken to determine the reliability of these effects (Baum & Pew, in preparation). The clearest results come from the following paradigm: The primary task was to count backwards from a 3-digit number by either 7, 3, 1 or 0 (this latter condition consisted of saying the three-digit number repeatedly). On each trial the experimenter first told the subject what to count by and then read the subject a randomly chosen 3-digit number. The subject began counting and after three counts the tracking trial was initiated. Counting was done in time to the beat of a metronome. The metronome was deliberately set so that the counting rate for sevens was comfortable and virtually error-free. The same counting rate was then used for all levels of difficulty. The results of this experiment indicate that, in general, tracking performance worsens with increases in counting task difficulty. Performance of repeated and, in this case, random sequences was affected equally; that is, the repeated sequence performance retained its superiority over all levels of counting task difficulty, but it too was significantly worsened by counting. This suggests that there is an internal process contributing to the differential tracking performance. That is relatively independent of the process in which tracking and counting compete for limited resources. Thus far our experiments offer no clues as to exactly what kind of process is involved, but perhaps it is associated with strengthening the underlying representation of the repeated sequence rather than its execution.

We now turn to a discussion of what characteristics this process might have.

Suppose that we view the subject performing the tracking task as an error-correction device (Krendel & McRuer, 1960; Pew, 1970, 1974). The subject possesses internal processes for perceiving the signal and cursor, selecting and executing motor commands, and detecting errors. At any one moment, the subject perceives a discrepancy (which may be zero) between the actual and the desired performance (i.e., between the target and cursor position). When this error is perceived (the magnitude of the error and its rate of change) a motor command to correct it is selected and executed. These detection and output processes take time, called the processing delay. This processing delay may be regarded as the major deterrent to perfect performance and we hypothesize that the subject improves his performance by reducing the processing delays. (There is also a certain amount of noise on input--a detection problem--and on output--a motor tremor--which by themselves would prevent perfect performance.) How might this come about? Consider the random signals for the moment and note that in these experiments the process producing them passes low frequencies (below 2.0 rad/sec) with equal power, but has attenuated power at higher frequencies. Furthermore, this process produces a signal with a normal amplitude distribution. We propose that what the subject learns about the random sequences is that only a limited range of accelerations and velocities will be called for on output, some more frequently than others. Likewise, the amplitude of the output called for will distribute itself normally around zero. Thus, certain motor commands will come to have higher states of readiness than others. This reduction of uncertainty will reduce the processing delay associated with selecting the appropriate motor commands for error correction.

Now consider the repeated sequence performance. With the same constraints

on signal frequency and amplitude distribution there are now, in addition, specific sequences of amplitude, velocity, and acceleration that always follow one another. The positive transfer results (to the left arm as well as to the spatial inversion) suggest that something more than a specific chained sequence of motor movements is learned. We wish to call this series of commands a motor program. This command information does not exist independently for arbitrarily small sequences of output, rather there must be storage of relations among sequences. Improvement is accounted for by hypothesizing a hierarchical process by which sets of output commands are organized at a higher level, thus increasing the availability of the motor program. What is learned might be stored in the following form: if the response sequence is presently in a state having y velocity with z acceleration at x amplitude, then it will next move with z' acceleration profile to x' amplitude, and so on. It is not clear how long these sequences can be. Their length will likely depend upon saliencies in the input-response sequence and, therefore, some sequences or parts of sequences will be learned more rapidly than others. Learning of unrepeated, i.e., pseudo-random sequences, on this hypothesis, differs only by a matter of degree.

In summary, these experiments involving tracking of repeated sequences indicate that in the process of learning the fixed pattern, the subjects are learning something more general than just the pattern features. It is as if they learn a schema or set of rules for generating the pattern and then under certain circumstances can adjust certain parameters (e.g., direction) of the pattern to produce a match with the desired pattern.

The final experiment in this series approaches directly the question of what is learned when one experiences distortions of a specific prototype movement pattern. It has often been observed that no two (goal-oriented) movement patterns are ever exactly the same. At issue here is what kind of

internal representation permits the accomplishment of the same goals in terms of different motor patterns.

In this experiment subject tracked signals in which were embedded amplitude distortions of a specific "repeated" sequence. That is, each trial contained a variant of the prototypical pattern. During acquisition subjects tracked 24 different variants of the prototype, once each day for 12 days. They were then transferred to a condition in which one-half of the trials were prototypes and one-half were new variants. Initial results indicate that tracking of the prototypical sequence is better than old or new distortions despite the fact that subjects have never tracked it before. Thus, it appears as if the nervous system extracts a motor program or schema for the prototypical sequence which in fact is approximately the mean of the variants. These results are consistent with those found in research on pattern perception (Posner & Keele, 1968; Reed, 1972). We conclude that the notion of schematic information representation captures in a qualitative way the general nature of memory system storage both for input and output purposes.

Time Sharing

Finally, we have examined in one major study (Wickens, 1974) the effects of extensive time sharing activity within the context of feedback control theory. In much of the research on time-sharing, the effects of diverted attention on task performance is assessed either by very global measures (e.g., error rate), or by the highly specific measure of an increase in processing time (e.g., reaction time). There is evidence, however, that other effects of diverted attention, such as an increase in internal processing noise, or a cognitive change in processing strategy, exist, but may only be revealed by a more detailed analysis of task performance. The purpose was to examine these time-sharing effects in a manual tracking paradigm, employing the fine-grained analysis provided by the techniques of feedback control theroy. This theroy appears to establish the presence of both time-delay and noise-addition effects of time sharing.

The subjects each performed three information-processing tasks under seven time-sharing conditions. The tasks employed were compensatory tracking of a random-appearing input, auditory signal detection, and application of a constant force with the non-tracking hand. Each task was performed singly, and in combination with one and with both of the other two tasks. Tracking performance was described by the Crossover Model of McRuer and Krendel (1959) and the remnant model of Levison, Baron and Kleinman (1969). The various performance parameters measured included three that assessed, in each task, the level of internal noise added to the processing of the signal. These parameters were the d' measure of signal detection, the magnitude of error power in the force task, and the level of remnant (output signal power that is uncorrelated with input) in the tracking task. Tracking mean squared error and the Crossover Model parameters measuring tracking gain and effective time delay were also determined.

The results indicated that all tasks showed both performance decrements and processing-noise increases under some time-sharing conditions. Time-sharing interference, however, was most evident between the response aspects of the tasks, and the noise-level increase in the tracking task was concluded to result from motor, rather than perceptual, processing interference. A decrease in the tracking gain parameter was obtained, but there was no consistent increase in the measure of time delay under the various time-sharing conditions. These results were interpreted in terms of the parameter effects on the subject's tracking stability, and in terms of a limited-capacity concept of time-sharing performance. The interpretation most consistent with the results viewed the subjects processing behavior as a hierarchy of control loops. At the lowest level of the hierarchy -- the basic operator describing the function plus remnant-- noise level, and under some conditions time delay, are automatically determined by the time-sharing load. At a higher cognitive level, however, adaptive

adjustments of gain, and possibly time delay, are made to compensate for these lower level effects, in order to maintain system stability, or achieve some other performance goals.

THE ANALYSIS OF THE EFFECTS OF SPEED STRESS

An extensive program of research has been conducted within the present project that is intended to understand and localize the effects of speed stress. Speed stress has been defined for the most part as the unrealistic demand for the subject to produce fast responses. Work on this project has involved two related lines of research. One involves the attempt to specify the nature of the input processing system under general speeded conditions. Here we have relied heavily on what has come to be called additivity analysis or the Additive Factor Method. The purposes of these studies has been the careful specification of the normal mode of information processing the second line of research has been oriented toward taking this processing system and subjecting it to enormous demands for speeded performance in order to see how the accuracy of performance declines both quantitatively and qualitatively. In pursuing this work we have had to develop both new methodological and and analytic techniques of error analysis. The convergence of the two lines of research will ultimately lead to a comprehensive theory of both the operation of the human information processing system in perceptual encoding tasks and the specification of the effects of speed stress within that system. The present project has brought us close to this final synthesis, but we are still somewhat short of this goal.

A. Additivity analysis of reaction time.

The long-term objective of this research has been to identify the sub-processes of perceptual encoding, to specify their progress in real time, and to find out their interconnections. One of the important working assumptions of current methodology is that factors which affect different processes have additive effects on reaction time. However, a series of experiments based

on this assumption has forced us both to partition the perceptual encoding process into two subprocesses, and to modify the additivity assumption, as regards these two subprocesses: apparently, they operate partly in a parallel mode, and factors which affect them separately are therefore underadditive Pachella (1976).

The additive-factors method. A fundamental concept underlying most reaction time paradigms is the notion that an independent variable that increases reaction time does so by increasing the duration of one or more of the component processes that make up the task or that introduces new operations into the mediating sequence. The modeling of this assumption has a long and controversial history. The earliest attempt, developed by Donders in 1868 and now widely known as the subtraction method, assumed that one could isolate the duration of a component mental process by producing a control task that differed from the experimental task by the elimination of the process in question. Although often used, there are severe limitations to the interpretability of this method (see Sternberg, 1969, or Pachella, 1974, for discussion). Sternberg (1969) developed an alternative approach, the additive-factor method, which is more intuitively appealing and simpler in its assumptions. This method models the results of multi-factor reaction time experiments. It is assumed that changes in reaction time that result from going from one level of a given factor to another are produced by changing the durations of the various component processes, without changing sequencing of the processes themselves. Patterns of additivity and interaction are then used to delineate the nature of the processes. Two factors that affect temporally discrete processes will produce additive effects on reaction time. Factors which mutually modify each others' effect, i.e., which produce interactions, are assumed to have some common locus of effect. These patterns of interaction thus serve to define the nature of the processes in question, since it must mediate or account for the effects of the set of factors that modify its duration, while patterns of additivity serve to define the

boundaries between stages.

This approach to theorizing has proven effective, particularly in developing initial conceptualizations of the processing underlying some particular task. While these first approximations often work simply in an operational sense, there are often present patterns of interaction that have no face validity or that simply make no logical sense. In these cases the initial model serves a normative function, defining the places where the assumptions must be changed or where new modes of theorizing must be applied. It is from this perspective that a long series of experiments (Miller & Pachella, 1973,1976; Pachella and Miller, 1976) has been conducted within our laboratory.

The separation of encoding from memory scanning. In attempting to delineate the boundaries of stimulus encoding processes, the memory scanning paradigm developed by Sternberg (1966, 1967) has proved very useful. Sternberg first proposed that the linear slope of reaction time as a function of set size reflected the operation of the first post-encoding operation, an operation that scanned the items that were being held in memory. The intercept of this memory scanning function was taken to reflect both the encoding processes and the response processes. Two aditive factor observations have strengthened this conclusion. First, Sternberg (1967), Bracey (1968) and Hardzinski & Pachella (1976) have all shown that both stimulus contrast and visual noise affect only the intercept of the memory scanning function. Thus, unless these factors, which are compelling relative to defining encoding activities, have some effect on post-memory scanning operations, their effects can be assumed to be confined to the initial or pre-memory scanning stage. Second, Wattenbarger and Pachella (1972) demonstrated that the effect of number of items in the memory list (memory load) had effects that were confined to the scanning operation and in particular did not affect the initial encoding stage. This demonstration involved intermixing memory scanning trials and choice reaction time trials, where the subject could not know what type of trial he was on until he had encoded the

probe character. Had memory load affected the encoding operation an effect of memory load would have appeared on the choice reaction time trials. No such effect was found. Thus, these two observations taken together form a powerful tool in reasonably defining the limits of the encoding stage and in particular, designate stimulus contrast and visual noise as important operational factors in localizing the effects of other variables within or outside of the encoding stage.

Central factors that affect encoding. One factor that has been of great importance in the attempt to explicate the nature of stimulus encoding operations has been stimulus probability. For many years, a fundamental question in the study of perception has been the question of whether or not stimulus probability which is not a property of the physical stimulus present on a particular trial, affects the manner in which external information is internalized. Within the microcosm represented by the memory scanning paradigm the study of this issue has been instructive both with regard to the question about the nature of the encoding processes and also the question of the usefulness of the additive-factor method.

Theios (1973) argues that the effect of the probability of the probe character in the memory scanning paradigm was on the memory search operations. He believed this on the basis of the presence of dramatic effects of probe probability on reaction time and constructed a model in which the memory list was searched in a manner that reflected the probabilities of the various stimuli. Miller and Pachella (1973), however, demonstrated that the effect of probability was modified by the contrast of the probe stimulus, (much larger effects of probability are observed with low contrast stimuli). Since the effect of contrast is limited to the encoding stages, it would seem that at least a part of the effect of probability is in the encoding stage.

An important and complementary finding to that of Miller and Pachella (1973) would be to vary stimulus probability and memory load orthogonally in order to

see if the effects of probability are confined to the encoding stage or if there is also a locus of this effect in the memory scanning stage. Two studies (Biedeman & Stacy, 1974; and Theios & Walter, 1974) have attempted to make this demonstration with ambiguous results. The ambiguity is indigenous to the nature of these two variables and points not only to the difficulty of this type of experiment but also to an important additional variable. The problems with varying probability and memory load orthogonally is the fact that memory load itself involves a manipulation of stimulus probability. That is, under normal circumstances each item in the memorized list is presented as the probe equally often. However, the more items in the list, the less often will any particular stimulus appear as the probe. Thus memory load itself becomes a manipulation of probability, and the attempt to mix these two variables orthogonally becomes logically most difficult.

An important fact to note about the above relation involves recalling that Miller and Pachella (1973) found an interaction of probability with contrast, while Hardzinski and Pachella (1976) found that contrast does not interact with memory load. Thus, it is not the absolute probability of the probe that seems to effect the encoding stage, but the relative probability of the probe. That is, even though stimulus probability naturally covaries with memory load, on any given trial all of the relevant stimuli on that trial are equally likely.

There is no expectancy that one of the items has a higher probability of appearing than any other item on that trial, even though there is a higher probability of any particular item than there is on a trial with a larger memory set, and a lower probability than any particular item on a trial with a smaller memory set. Thus, probability and expectancy need to be differentiated.

Two studies ahve attempted to produce this differentiation. Klatzky and Smith (1972) varied set size and expectancy by indicating during the presentation of the memory set that one of the items was more likely to appear as the probe than the other items. They found the two variables to have independent effects.

Wright and Pachella (1976) manipulated rehearsal recency by having the subject rehearse the target set in synchrony with flashed rehearsal cues. They found that the character most recently rehearsed was responded to more quickly than the other characters in the target set and that this effect was also independent of memory set size.

The representation of encoded items and peripheral factors that affect it. The nature of the representation arrived at during the encoding process has also been studied with the memory scanning paradigm. Wattenbarger (1970) demonstrated that the code normally used in the memory scanning operation involves a representation with the properties of the name of the stimulus. This demonstration consisted of varying the case of the memorized letters and the case of the probe stimulus. In one condition case was relevant to the subject's response, and in another condition case was irrelevant, that is, only the names of the stimuli determined the response. This latter condition gave results identical with a control condition that was run in the typical fashion where case was not varied. The former conditon yield much steeper slope of the memory scanning function, as well as a larger intercept. Thus, when physical information must be encoded and scanned the processing is much slower. Recently, Hardzinski and Pachella (1976) replicated Wattenbarger and also manipulated the contrast of the probe stimulus. Their results showed that in the name match condition contrast did not interact with memory load, a fact consistent with the control conditions, but contrast did interact with memory load in the physical match condition, but contrast did interact with memory load in the physical match condition. This fact is consistent with the idea that in this condition the representation used by the subject is some form of template and thus some of the effect of contrast is found in the memory scanning stage.

Partition of encoding. Finally, a recent finding that will be of some importance to the attempt to elucidate the subprocesses within the encoding stage is Miller's (1976) finding that visual noise and stimulus contrast have independent effects on encoding. Since Sternberg (1967) and Bracey (1969) has beoth found that visual noise is independent of set size, it seems reasonable to believe that Miller's finding indicates a partitioning of the encoding stage itself. The two subprocesses described by Miller involve a very early process that involves holistic, pre-attentive discrimination and a somewhat later process that carries out a form of feature analysis on the stimulus. These results provide another analytic tool for the further refinement of the locus of the effects of other variables most particularly, stimulus probability and expectancy.

B. Analysis of confusion errors under speed stress.

The long-term objective of this work has been to identify subprocesses of perceptual encoding, to specify their progress in real time, and to find out their interconnections. Current methodology, however, lies under the spell of an unworkable conception, namely, that each mental subprocess requires a definite (average) time for completion. The phenomenon of speed/accuracy tradeoff indicates that this idea will not work; rather, each subprocess may be more or less complete, depending on the time allowed. Incompletion shows up in the pattern of errors.

Our immediate goal has been to develop further a theory of stimulus confusion, and to study how the parameters of the theory vary under speed stress (short deadlines for response). This will help overthrow the current unworkable conception, by showing in detail how speed/accuracy tradeoff works and by offering an alternative methodology for isolating and examining mental subprocesses.

The measurement of reaction time has become one of the basic tools in the analysis of information processing. Suppose, for example, that some variable

is changed which makes an information-processing task a bit harder, and that consequently, the average reaction time is a bit longer. This increased reaction time is assumed to represent the added time to complete certain mental processes which are affected by the variable which was changed. The underlying assumption is that for each task, and indeed for each subprocess, there is some special value of time, namely, the minimum (average) time needed to complete the task or subprocess properly, given the circumstances. This "minimum proper time" varies when the task is altered slightly, and these variations show up in the measured reaction time.

There is much reason to question the "minimum proper time" assumption Pachella (1974). The alternative view is that each task, and indeed each subprocess, can be completed better or worse, taking various amounts of time. This view leads to the idea of a speed/accuracy tradeoff function (SATF): if a subject is forced to go a bit faster, subprocesses are less complete or may even drop out and be substituted by other faster ones, and errors occur more numerously. From this point of view, there is a much better research strategy for understanding mental processes. Instead of measuring how long it takes to "complete" the process, it is better to vary systematically the time taken and see how the output of the process alters as it becomes more complete or less complete. In this approach, it is necessary to measure not only the numerousness of errors, but their kind. In a two-choice task there is only one kind of error possible on any given trial, i.e., the wrong choice; therefore this approach must be pursued with n-choice tasks, $n > 2$, to allow different kinds of errors and to see how the kinds of error change as the time for the task changes.

The unsoundness of the former "minimum proper time" assumption is indicated by the ubiquity of SATF's, and especially by the fact that when the error rate is low, as it usually is, the SATF is very shallow, so large time differences may be caused by slight adjustments of error rate. A host of recent studies (e.g., Pachella, 1973) have shown that reaction-time differences have been partly

misinterpreted due to changes in accuracy. These misinterpretations include misstatements of the effects of warning signals, repetitions, memory load, alcohol consumption, and aging on mental processing. In view of these disasters, it seems necessary at this point to pursue the alternative strategy outline above: vary the time available to complete a task and try to infer the output of various subprocesses from the variation in number and kinds of errors. (For recent criticisms and conclusions, see Ollman, 1976, Pachella, 1974, and Wickelgren, 1974.)

Pursuing the alternative strategy just sketched, we must analyze kinds of errors. Unfortunately there is an immediate complication. Assume we perform an identification experiment with stimuli 1,...,n and responses 1,...,n and with response i correct only when stimulus i is presented. Suppose that on a given trial stimulus i is presented and an error response j occurs. There are two factors that cooperate to make this happen: confusion of stimulus i with stimulus j, and a bias toward using response j. In fact, both factors are needed: if the information processing eliminates stimulus j, this particular error should not occur; or if response j is unpopular, once again this error is unlikely. Thus we are led to model the probability of this error as a product of two quantities: one quantity summarizes the poorness of information processing and the similarity of stimuli i and j; the other one reflects the popularity of the particular response. Several quantitative models along this line have been proposed: the biased choice model (Luce, 1963); the sophisticated guessing model (Broadbent, 1967); and the overlap model (Townsend, 1972). We also consider a model which falls inbetween Broadbent's and Townsend's, which we call the informed guessing model. We have done considerable work on the problems of identifiability and parameter estimation for these various models These models are useful to us because they propose separate estimates of information-processing parameters and response-popularity parameters, and we can observe how these separate estimates change as a function of task variables, including

time deadline.

Stanovich, Smith, and Pachella, (1975), randomly presented 1 of 6 letters visually and had the subject name it, imposing deadlines of 360 msec or 410 msec. The confusions among letters were meaningful, rather than just guesses; Luce's biased choice model fit the data well at both deadlines; and the response biases remained about the same, across deadlines, while the stimulus similarity parameters increased at shorter deadline. Thus, we are led to the idea of an expanded SATF: for each stimulus similarity parameter, we can plot its decrease (more accuracy) as processing time increases. Further validation came from a condition in which contrast was reduced: this increased the similarity parameters also, leaving response biases more or less invariant. Finally, we manipulated stimulus probability (and hence, response probability). The affected both sets of parameters.

Pachella, Smith and Stanovich (in press) also used voiced naming of single visually presented letters, but now had 4 letters, B,C,D, and E, in a type font (Rumelhart, 1971) in which B and D are similar and E, C are similar but there is little confusability of the other 4 pairs. We used the informed guessing model which has probability parameters for full recognition of each stimulus, for pairwise uncertainty (the subject has enough information to eliminate all but two letters, but must then guess between them), and for complete uncertainty (pure guessing.) We studied 4 deadlines (340 to 525 msec) to obtain the SATF's more exactly. The model fit well, the full-recognition parameters increased with time, the pairwise-uncertainty and complete uncertainty parameters decreased with time, and the response biases were nearly constant. Only the B,D and E,C pairwise uncertainties were appreciably different from zero, and other details of parameters were also well predicted from details of the type font.

These results show that we can trace out the time course of mental processes (such as identification of critical stimulus features, etc.) by

observing the changes in a parameter of an error model, as the task deadline changes.

Three additional results have been obtained within the current project: First we showed that changes in stimulus probabilities affected only response-bias, not uncertainty parameters. Second, we explored a more extreme speed-stress condition and showed that other pairwise uncertainties besides B,D, and C,E, begin to emerge as responding becomes very fast. Finally, we compared deadline conditions with tachistoscopic recognition of the same four letters. Here, there is no time pressure, but processing is limited by the input brevity. We found greatly increased B,D and C,E uncertainties, but decreases both in complete uncertainty and in full-recognition probabilities in the tachistoscopic experiment. All these results make a good deal of sense and confirm that we ahve struck a combination of method and model that can provide a detailed analysis of perceptual information processing.

TEST BATTERY OF HUMAN PERFORMANCE

Over the past ten years of ARPA supported activities at the Human Performance Center, we have developed considerable expentise isolating of component mental processes by the judicial use of experimental paradigms. The development of a test battery of human performance has represented the attempt on our part turn this expertise to the question of the application of research on human information processing capacities and limitations to the problem of performance assessment. Specifically, the goal of the present effort was the establishment and empirical verification of a test battery that could be used to evaluate performance in a wide variety of situations, and that could provide information concerning basic processing capacities.

The basic strategy employed in this research project was to select experimental or research paradigms from the psychological literature that have firm theoretical and empirical bases. The primary criterion for test selection was construct validity: there was a high a priori expectation that a given paradigm or experiment actually measured that aspect of human performance which it was intended to measure. Selected tasks were adapted to feasible formats. They were then combined into a battery and administered as a pilot study. Four small-scale experiments were performed to refine the paradigms of selected tasks. A final battery was then assembled, and a large-scale (100Ss) "validation" experiment was performed. The goal of this strategy was to define a set of statistically independent tests, each of which had high construct validity and high reliability.

The above strategy resulted from a review of three existing methodologies for performance assessment: (1) task simulation, (2) synthetic work environments, and (3) factor-analytically derived "specific-test" techniques. Each of these approaches was examined and found to have limitations, either due to a weak theoretical foundation or to a lack of empirical support.

Based on the results of the literature review and the pilot studies, the tasks employed in the final validation experiment were the following:

1. The Stroop test
2. Continuous paired-associate memory task
3. "Critical" tracking task
4. Fitts' tapping task
5. Speed-accuracy reaction-time task
6. Worked-recognition threshold
7. Neisser letter-search task
8. Grammatical-reasoning (A-B) task
9. Rotated-letters task

The final validation experiment (Rose, 1974) demonstrated that these tasks were (for the most part) reliable and statistically independent. Furthermore, the theoretical foundations of these tasks, along with correlational, factor-analytic, and regression analyses performed in the present study, indicated that each task had high construct validity.

Finally, the Rose (1974) study has provided procedures for implementation and administration of the battery. Descriptive statistics (means, standard deviations, standard errors, range of test scores), along with obtained reliability estimates and intercorrelation matrices, presented. Thus, an empirical data base that can be used as a reference for future experimentation has been established.

Several independent attempts to apply the battery have been supported by the research project. This support has involved material, manpower and general consulting capabilities of the Human Performance Center. In several instances this support has been granted without proprietary obligation: Our purpose has been to establish the test battery in the general research community and thus, to expand its validation base while minimizing the Center's role in the actual conduct of the research. One completed study (in collaboration with Dr. George Brewer, University of Michigan Medical School) involves the study of the ability of a particular drug to overcome the effects of high altitude anoxia. Appropriate experimental and control groups were administered the test battery both in Ann

Arbor and at the top of Pike's Peak. The results of the study indicated differential effects on various battery tests as a result of transportation from Ann Arbor to Pike's Peak, but no effect of the administered drug.

Two further studies, for which results have not yet been completely obtained, involved first (in collaboration with Dr. Lowell Goodman of Parke-Davis, Inc.) the question of the effect of the tranquillizers Valium and Librium on complex perceptual-motor performance (e.g., automobile driving). It is hoped that differential effects of these drugs will appear on the perceptual, cognitive and motor components of the test battery. The second formulated validation study (in collaboration with Dr. Gerald Gardner, University of Michigan, Dearborn Campus) attempts to localize within component mental processes the effects of environmental noise pollution. Finally, we have been contacted by Dr. Edward Domino of the University of Michigan Medical School to work out a study that attempts the assessment of the effects of alcohol on performance and the transfer of alcoholic experience to new intoxicants (e.g., marijuana) by chronic users.

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V. SUMMARY

This is the Final Technical Report on Contract F44620-72-C-0019 between the Advanced Research Projects Agency, Department of Defense, monitored by the Air Force Office of Scientific Research, and the Human Performance Center, Department of Psychology, University of Michigan, for research on Human Information Handling Processes during the period 1 OCT ~~June~~ 1971 ~~1967~~ to 30 June ~~August~~ 1971. The report lists the products of contract work: 41 technical reports published and 25 oral presentations at scientific meetings. Major accomplishments are summarized under the general headings of (a) State (of the organism) Variables (b) Information Overload (c) Speed Stress and (d) a Test Battery of Human Performance.